Our Galaxy
(Milky Way)

Distant Galaxies
Now

Distance
Our Galaxy (Milky Way)

Distant Galaxies

Earlier

Now

Distance
Our Galaxy (Milky Way)

Distant Galaxies

Earlier

Now

Distance

Velocity
Distance away from us

Velocity away from us

Distance away from us
The original Hubble Diagram

“A Relation Between Distance and Radial Velocity Among Extra-Galactic Nebulae”

E. Hubble (1929)
The original Hubble Diagram

“A Relation Between Distance and Radial Velocity Among Extra-Galactic Nebulae”
E. Hubble (1929)

Edwin Hubble
American
Galaxies outside Milky Way
The original Hubble Diagram

“A Relation Between Distance and Radial Velocity Among Extra-Galactic Nebulae”
E. Hubble (1929)

Edwin Hubble
American
Galaxies outside Milky Way

Henrietta Leavitt
American
Distances via variable stars
Hubble Relation

\[ v = H_0 d \]
Hubble Relation

\[ v = H_0 d \]

<table>
<thead>
<tr>
<th>Year</th>
<th>( H_0 ) km/sec/Mpc</th>
</tr>
</thead>
<tbody>
<tr>
<td>1929</td>
<td>(~500)</td>
</tr>
<tr>
<td>2001</td>
<td>72 +/- 7</td>
</tr>
</tbody>
</table>


W. Freedman
Canadian
Modern Hubble constant (2001)
Time ($t$)

Position ($x$)

Milky Way (ie Us)

Now
Time ($t$)

Other Galaxies

Milky Way (ie Us)

Position ($x$)

Now
Time ($t$)  

Position ($x$)

Now

Other Galaxies

Milky Way (ie Us)
Time ($t$)  |  Position ($x$)

Now  |  Other Galaxies  |  Milky Way (ie Us)

...
Time ($t$)

Other Galaxies

Milky Way (ie Us)

Position ($x$)

Now

Big Bang?
Time \( t \)   \[ \text{Other Galaxies} \quad \text{Milky Way (ie Us)} \quad \text{Position (} x \text{)} \]

Age of the Universe

\[ = \frac{1}{H_0} \]

Big Bang?
Time ($t$)

Other Galaxies

Milky Way (ie Us)

Position ($x$)

Now

Age of the Universe

$= 1/H_0$

$\sim 10^{10}$ year

Big Bang?
Now
Now

Earlier
Now
Earlier
Now
Earlier

Velocity
Distance
Now

Earlier

Velocity

Distance

Velocity

Distance
Now

Earlier

Same Hubble pattern seen from *any* galaxy!
Looks the same in all directions
Looks the same in all directions

Isotropy
Hubble expansion

\[ v = H_0 d \]
Hubble expansion

$v = H_0 d$

Same pattern seen from any galaxy

Isotropy

Looks the same in all directions
Hubble expansion

$v = H_0 d$

Same pattern seen from any galaxy

Isotropy

Looks the same in all directions

Uniformity
Hubble expansion
\[ v = H_0 d \]

Same pattern seen from any galaxy

Isotropy
Looks the same in all directions

Uniformity
The Universe is (pretty much) the same everywhere!
Time ($t$)

Other Galaxies

Milky Way (ie Us)

Position ($x$)

Now
Time ($t$)

Other Galaxies

Milky Way (ie Us)

Position ($x$)

Now
Time $(t)$

Other Galaxies

Milky Way (ie Us)

Position $(x)$

Now
Time ($t$)  

Other Galaxies  

Milky Way (ie Us)  

Position ($x$)

Now

10 M Lyr

5 M Lyr
Universal Scale Factor

\[ a(t) = \frac{\text{Distance}(t)}{\text{Distance}(\text{Now})} \]
Universal Scale Factor

\[ a(t) = \frac{\text{Distance}(t)}{\text{Distance}(\text{Now})} \]
Universal Scale Factor

\[ a(t) = \frac{\text{Distance}(t)}{\text{Distance}(\text{Now})} \]

Evolution of homogeneous, non-static (expanding) universes

“Friedmann models” (1922, 1927)
Motion of Light

Time (t)

Now
Motion of Light

Now

Time \( (t) \)

100 MLYr

100 Myr
Motion of Light

Time ($t$)

Now

100 MLyr

100 Myr
Motion of Light

Time \( (t) \)

Now

100 MLYr

100 Myr
Motion of Light

Time ($t$)

Now

100 Myr

50 Myr
Motion of Light

Time ($t$)

Now

100 MLYr

100 Myr

50 MLYr

50 Myr
Motion of Light

Time ($t$)

Now

Photon Path
Motion of Light

Photon Path

Now

Time ($t$)

Slope = 0
a(t)=0
Motion of Light

Photon Path

Now

Big Bang

Time ($t$)

Slope = 0

$a(t) = 0$
Motion of Light

Now

Time ($t$)

Big Bang

Age of the Universe

Photon Path
Motion of Light

Time ($t$)

Size of the Observable Universe

Now

Big Bang

Age of the Universe

Photon Path
Cosmological Red Shift

A Photon Path
Cosmological Red Shift
Cosmological Red Shift
Cosmological Red Shift

Several possible photon paths
Cosmological Red Shift
Cosmological Red Shift
Cosmological Red Shift
Cosmological **Red Shift**
Cosmological Red Shift

\[
\lambda(t_{\text{Observed}}) / \lambda(t_{\text{Emitted}}) = a(t_{\text{Observed}}) / a(t_{\text{Emitted}})
\]
The Accelerating Universe

Part 2
Now

No De/Acceleration

Normal Matter
Deceleration
Need: Distance/Time versus Redshift for very distant, very ancient events/sources
Riess, et al. (High-Z)

A. Riess
American
Supernovae cosmology (1998)
Riess, et al. (High-Z)

A. Riess
American
Supernovae cosmology (1998)
Riess, et al. (High-Z)
A. Riess
American
Supernovae cosmology (1998)

Riess, et al. (High-Z)
A. Riess
American
Supernovae cosmology (1998)

\[
z = \frac{\lambda(t_{\text{Observed}})}{\lambda(t_{\text{Emitted}})} - 1 \approx \frac{v}{c}
\]

Riess, et al. (High-Z)
MLCS

- Decelerating (hyperbolic)
- Decelerating (Euclidean)

- Open: $\Omega_m = 0.20, \Omega_\Lambda = 0.00$
- Generic: $\Omega_m = 1.00, \Omega_\Lambda = 0.00$
MLCS

\[ m - M \text{ (mag)} \]

\[ \begin{align*}
\Lambda \neq 0 & \quad \Omega_M = 0.24, \; \Omega_\Lambda = 0.76 \\
\text{Open} & \quad \Omega_M = 0.20, \; \Omega_\Lambda = 0.00 \\
\text{Generic} & \quad \Omega_M = 1.00, \; \Omega_\Lambda = 0.00
\end{align*} \]
Expansion History of the Universe


After inflation, the expansion either...

- first decelerated, then accelerated
- or always decelerated

...past or always decelerated...

redshift

0.0001 0.001 0.01 0.1 1

Billions Years from Today

a(t)

Scale of the Universe Relative to Today's Scale

expands forever

collapses

0 0.5 1 1.5 2 3

z
Expansion Dynamics

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G_N}{3c^2} \left[ \rho(t) + 3P(t) \right]$$

The Friedmann Equation
Expansion Dynamics

\[
\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G_N}{3c^2} \left[ \rho(t) + 3P(t) \right]
\]

Mass-Energy Density

The Friedmann Equation
Expansion Dynamics

\[ \frac{\ddot{a}(t)}{a(t)} = - \frac{4\pi G_N}{3c^2} \left[ \rho(t) + 3P(t) \right] \]

The Friedmann Equation

\[ \begin{align*}
\ddot{a}(t) &= -\frac{4\pi G_N}{3c^2} \left[ \rho(t) + 3P(t) \right] \\
\rho(t) &= \text{Mass-Energy Density} \\
P(t) &= \text{Pressure} \\
\end{align*} \]
Negative Pressure (?)

Radiation
Negative Pressure (?)

Radiation

\[ P = -\frac{\partial E}{\partial V} = +\frac{\rho}{3} \]
Negative Pressure (?)

Radiation

\[ P = -\frac{\partial E}{\partial V} = +\frac{\rho}{3} \]

Matter
Negative Pressure (?)

**Radiation**

\[ P = -\frac{\partial E}{\partial V} = +\frac{\rho}{3} \]

**Matter**

\[ P = -\frac{\partial E}{\partial V} \sim 0 \]
Negative Pressure (?)

Radiation: \[ P = -\frac{\partial E}{\partial V} = +\frac{\rho}{3} \]

Matter: \[ P = -\frac{\partial E}{\partial V} \sim 0 \]

Vacuum Energy
Negative Pressure (?)

**Radiation**

\[ P = -\frac{\partial E}{\partial V} = +\rho/3 \]

**Matter**

\[ P = -\frac{\partial E}{\partial V} \sim 0 \]

**Vacuum Energy**

\[ P = -\frac{\partial E}{\partial V} = -\rho \]
\[
\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G_N}{3c^2} [\rho(t) + 3P(t)]
\]
\[
\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G_N}{3c^2} \left[ \rho(t) + 3P(t) \right]
\]

Radiation \quad a(t) \propto t^{1/2}

Matter

Vacuum Energy
\[
\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G_N}{3c^2} \left[ \rho(t) + 3P(t) \right]
\]

**Radiation**

\[a(t) \propto t^{1/2}\]

**Matter**

\[a(t) \propto t^{2/3}\]

**Vacuum Energy**
\[ \frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G_N}{3c^2} \left[ \rho(t) + 3P(t) \right] \]

Radiation \[ a(t) \propto t^{1/2} \]

Matter \[ a(t) \propto t^{2/3} \]

Vacuum Energy \[ a(t) \propto e^{H_0 t} \]
It appears to be some entirely new form of energy.
The New Standard Cosmology in Four Easy Steps

Inflation, dominated by “inflaton field” vacuum energy

\[ a(t) \propto e^{Ht} \]
The New Standard Cosmology in Four Easy Steps

- Inflation, dominated by “inflaton field” vacuum energy
- Radiation-dominated thermal equilibrium

\[ a(t) \propto e^{Ht} \]

\[ a(t) \propto t^{1/2} \]
The New Standard Cosmology in Four Easy Steps

- Inflation, dominated by "inflaton field" vacuum energy
- Radiation-dominated thermal equilibrium
- Matter-dominated, structure forms

\[ a(t) \propto t^{1/2} \quad a(t) \propto t^{2/3} \quad a(t) \propto e^{Ht} \]
The New Standard Cosmology in Four Easy Steps

1. Inflation, dominated by “inflaton field” vacuum energy
   \[ a(t) \propto e^{Ht} \]

2. Radiation-dominated thermal equilibrium
   \[ a(t) \propto t^{2/3} \]

3. Matter-dominated, structure forms
   \[ a(t) \propto t^{1/2} \]

4. Acceleration, return cosmological constant and/or vacuum energy.
Euclidean Vacuum Energy $\Lambda \neq 0$

Hyperbolic
Euclidean Vacuum Energy $\Lambda \neq 0$

Hyperbolic Vacuum (i.e. Dark) Energy Density

Vacuum (i.e. Dark) Energy Density

$\Omega_\Lambda$

$\Omega_M$

MLCS

Expands to Infinity

Accelerating

Decelerating

$\Omega_\Lambda = 1$

$\Omega_{\text{MLCS}}$
Euclidean Vacuum Energy $\Lambda \neq 0$

Hyperbolic Vacuum (i.e. Dark) Energy Density

Matter Energy Density

Vacuum (i.e. Dark) Energy Density

$\Omega_\Lambda$

$\Omega_M$

No Big Bang

95.4%

99.7%

99.7%

68.3%

MLCS

Accelerating

Decelerating

$q_0 = 0$

$q_0 = 0.5$

Expands to Infinity

$\Omega_{0\Lambda} = 1$

Closed

Open

Recolapses

$\Omega_{0\Lambda} = 0$

0.0

0.5

1.0

1.5

2.0

2.5

0

1

2
Euclidean Vacuum

Hyperbolic Vacuum (ie Dark) Energy Density

Matter Energy Density

Vacuum Energy \( \Lambda \neq 0 \)

Euclidean

Hyperbolic

Expands to Infinity

Accelerating Decelerating

Decelerating

Closed Open

Closed

Recollapses

MLCS

No Big Bang

\( q_0 = 0.5 \)

\( q_0 = 0 \)

\( q_0 = 0.5 \)

Recollapses \( \Omega_{M} = 1 \)

\( \Omega_{M} = 0 \)
<table>
<thead>
<tr>
<th><strong>20^{th} Century</strong></th>
<th><strong>21^{st} Century</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Working Belief</td>
<td>20\textsuperscript{th} Century</td>
</tr>
<tr>
<td>----------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td></td>
<td>All matter, no dark energy</td>
</tr>
<tr>
<td>Working Belief</td>
<td>20\textsuperscript{th} Century</td>
</tr>
<tr>
<td>------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>All matter, no dark energy</td>
<td>Geometrically Euclidean</td>
</tr>
<tr>
<td>Key Observables</td>
<td>Matter density</td>
</tr>
<tr>
<td>Working Belief</td>
<td>20th Century</td>
</tr>
<tr>
<td>---------------</td>
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</tr>
<tr>
<td>Key Observables</td>
<td>Matter density</td>
</tr>
<tr>
<td>Unsettling Coincidence</td>
<td>Close to, but not quite, Euclidean</td>
</tr>
</tbody>
</table>
Modern Observables

Part 3
**$P(k)$**: how lumpy is your Universe?

**Figure 1.**

- **Top**: Data points showing inference of the 3D linear matter power spectrum at $z = 0$ from Planck CMB data on the largest scales, SDSS galaxy clustering on intermediate scales, SDSS Lyα clustering and DES cosmic shear data on the smallest scales. In cases where error bars in the $k$-direction are present, we have used the method of Tegmark & Zaldarriaga (2002) to calculate an $60\%$ central quantile of the region to which each data point is sensitive. In other cases, data points represent the median value of the measurement. The solid black line is the theoretical expectation given the best-fit Planck 2018 CDM model (this model also enters the computation of the data points themselves). The dotted line for reference shows the theoretical spectrum including non-linear effects.

- **Bottom**: Deviation of the data from the Planck best fit CDM model.

In Table 1, we list the values of the parameters used in the best-guess simulation, as well as the corresponding best-fit values measured in Chabanier et al. (2018), for a fit to the eBOSS 1D Lyα power spectrum combined with the Planck 2018 “TT+lowE” likelihood (Planck Collaboration et al. 2018). The best-fit model is in good agreement with the central simulation. The parameters that deviate the most from their central value are $\Omega$ and $\Omega_m$. We determine the biases $b_f$ for the best-fit model by computing the biases $b_g$ for the best-guess simulation, and we apply first-order corrections to account for the measured shifts in $\Omega$ and $\Omega_m$, using simulations where all parameters are kept to their MNRAS 000, 1–7 (2015) values.

**“Matter Power Spectrum” $P(k)$**

**Inhomogeneity:** Amplitude$^2$ of Fourier moment of matter distribution on spatial scale $k$.

Figure from Chabanier, Millea, Palanque-Delabrouille arXiv:1905.18103
CMB: “Piper at the Gates of Dawn”

Cosmic Microwave Background (CMB) is released when primordial EM plasma de-ionizes at $z \sim 1100$. Temperature pattern reflects matter distribution + sound wave oscillations.
Summary

The uniform, isotropic expanding Universe was first described in the 1920’s -- 1930’s
Summary

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During the 20th century, intense focus on matter density and geometry; no exotic energy imagined.
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Summary

The uniform, isotropic expanding Universe was first described in the 1920’s -- 1930’s.

During the 20th century, intense focus on matter density and geometry; no exotic energy imagined.

At the turn of the 21st century, distant supernovae show the Universe’s expansion to be accelerating, forcing us to entertain exotic “dark/vacuum energy”.

Constant dark/vacuum energy will dominate the Universe; but why is the transition happening now? and is the dark/vacuum energy really constant?
What Destiny Awaits

Part 4
\[ \left( \frac{\dot{a}(t)}{a(t)} \right)^2 = \frac{8\pi G_N}{3c^2} \rho_{\text{Matter}} \frac{1}{(a(t))^3} - \frac{k}{(a(t))^2} \frac{c^2}{a(t)} + \frac{\Lambda}{3} \text{DarkEnergy} \]

(Another) Friedmann Equation
\[
\left( \frac{\dot{a}(t)}{a(t)} \right)^2 = \frac{8\pi G_N}{3c^2} \frac{\rho_{\text{Matter}}}{(a(t))^3} - \frac{k \text{Curvature}}{(a(t))^2} c^2 + \frac{\Lambda_{\text{DarkEnergy}}}{3}
\]

(Another) Friedmann Equation

20th Century: Matter vs Curvature

\[
\left( \frac{\dot{a}(t)}{a(t)} \right)^2 = \frac{8\pi G_N}{3c^2} \frac{\rho_{\text{Matter}}}{(a(t))^3} - \frac{k \text{Curvature}}{(a(t))^2} c^2
\]
\[
\left(\frac{\dot{a}(t)}{a(t)}\right)^2 = \frac{8\pi G_N}{3c^2} \frac{\rho_{0,\text{Matter}}}{(a(t))^3} - \frac{k \text{Curvature} c^2}{(a(t))^2} + \frac{\Lambda_{\text{DarkEnergy}}}{3}
\]

(Another) Friedmann Equation

20th Century: **Matter vs Curvature**

\[
\left(\frac{\dot{a}(t)}{a(t)}\right)^2 = \frac{8\pi G_N}{3c^2} \frac{\rho_{0,\text{Matter}}}{(a(t))^3} - \frac{k \text{Curvature} c^2}{(a(t))^2}
\]

21st Century: **Matter vs Dark Energy**

\[
\left(\frac{\dot{a}(t)}{a(t)}\right)^2 = \frac{8\pi G_N}{3c^2} \frac{\rho_{0,\text{Matter}}}{(a(t))^3} + \frac{\Lambda_{\text{DarkEnergy}}}{3}
\]
Vacuum/Dark Energy Density

Matter Energy Density
Euclidean Vacuum Energy $\Lambda \neq 0$

Hyperbolic Vacuum/Dark Energy Density
Euclidean Vacuum Energy $\Lambda \neq 0$

Hyperbolic Vacuum/Dark Energy Density

Matter Energy Density
Euclidean Vacuum Energy

Hyperbolic Vacuum/Dark Energy Density

Matter Energy Density

$\Omega_{\Lambda} = 0$

Vacuum Energy

Expands to Infinity

Accelerating $q_0 = 0.5$

Decelerating $q_0 = 0$

Closed $\Omega_{\Lambda} = 1$

Open $\Omega_{\Lambda} > 1$

MLCS
Now

Big Bang

Observable Past

Matter

Dark Energy

Milky Way

Distant Galaxy

Time
Observed Past

Matter

Dark Energy
Now

Big Bang

Matter

Observable Past

Dark Energy
Now Big Bang

Matter

Dark Energy

Observable Past
Now
Big Bang

Observable Past

Matter

Dark Energy